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ESTIMATION OF SUPERFICIAL GAS VELOCITY IN A PILOT PLANT OPERATION

by

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ABSTRACT

This report contains the calibration of four orifices and a method to estimate the superficial gas velocity for planning the pilot plant operation.

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ÉVALUATION DE LA VÉLOCITÉ SUPERFICIELLE DU GAZ AU COURS DES PROCÉDÉS DE L'USINE PILOTE

par

D.D.S. Liu*

RÉSUMÉ

Le rapport comprend les résultats provenant du calibrage de quatre orifices ainsi qu'une méthode pour évaluer la vélocité superficielle du gaz en vue de préparer le plan d'exploitation de l'using pilote.

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INTRODUCTION

The gas flow rate is one of the most important parameters controlling the hydrodynamics in the CANMET hydrocracking process. In pilot plant operation, it is monitored by an orifice meter. The computation of volumetric rate for the orifice reading depends on the knowledge of gas density which is normally measured off-line after the experiment. It is shown here that the gas density can be estimated from correlations derived from previous experimental results.

Four orifices with equivalent diameters from 0.41 mm to 1.32 mm were calibrated. They can be used for calibrating new orifices.

MONITORING OF GAS FLOW RATE

The recycle gas in pilot plant operation is monitored by an orifice at room temperature (Fig. 1). The pressure drop across the orifice is continuously measured by a differential pressure gauge (D/P cell). The signal from the D/P cell is displayed by a Taylor meter with a strip recorder. The reading, R, is proportional to the square root of the pressure drop, ΔP, across the orifice.

$$R = K (\Delta P)^{1/2} \qquad \text{Eq. 1}$$

where K is a proportional constant.

The gas velocity is related to the pressure drop by (1):

$$u_o = [C_o/(1 - b^4)^{1/2}][2g_c \Delta P /d]^{1/2} \qquad \text{Eq. 2}$$

where

- b = ratio of orifice diameter to pipe diameter
- C_o = orifice coefficient
- d = density of fluid
- g_c = gravitational acceleration
- u_o = velocity through the orifice

Inserting Eq. 1 into Eq. 2:

$$u_o = (C_o/K)[2\, g_c(1 - b^4)\, d]^{1/2} R \qquad \text{Eq. 3}$$

The volumetric flow rate, V_G, at room temperature is:

$$V_G = u_o\, A_o$$

$$= (C_o/K)\, [2\, g_c/(1 - b^4)\, d]^{1/2}\, A_o\, R$$

$$= B\, R\, /\, d^{1/2} \qquad \text{Eq. 4}$$

where

A_o = area of the orifice opening
$B = (C_o/K)\, [2g_c/(1 - b^4)]^{1/2}\, A_o$

To ensure accuracy, value of B (a lumped constant) for each orifice must be determined experimentally.

CALIBRATION

Orifices were calibrated at ambient conditions against a wet test meter. Figure 1B shows the schematic of the setup for the calibration. Before calibration, the wet test meter, D/P cell and Taylor recorder were calibrated according to procedures recommended by the manufacturers.

A U-shape water manometer was installed parallel to the orifice (Fig. 1) allowing the direct measurement of relative ΔP which is slightly larger than that detected by the D/P cell because two more valves were used between the points of measurement. The inlet pressure of the wet test meter was monitored by a separate manometer, to ensure that no large deviation of inlet pressure from the recommended occurred.

A three-way valve was installed between pressure drop meters and the wet test meter. This allowed the gas to bypass and to reset the wet test meter. Nitrogen was used and the flow rate was controlled by two needle valves in series. When the gas bypassed the test meter, a constant flow rate

was obtained for a desired recorder reading (R in Eq. 1). The gas stream was then redirected toward the wet test meter and the measuring time started. Until the desired volume of gas had passed through the wet test meter, the duration of measurement was noted. By dividing the total volume of gas that passed through the meter by the time, the volumetric flow rate was determined.

There was no observable change in the reading when the gas stream was redirected from one route to another. This indicated that the additional resistance (pressure drop) caused by the test meter was small.

Results are summarized in Table 1. Figure 2 shows the plot of low rate against recorder reading. Good linear relations were obtained.

The constant K (Eq. 1) was set at 10 (inch of water)$^{-1/2}$ for the relation between the D/P cell and the Taylor instrument. As mentioned earlier the ΔP measured by the D/P cell and the U manometer were different, therefore their relation was measured separately.

The pressure drop measured by the manometer and the Taylor meter's reading, R, were recorded during the steady state operation. Results are summarized in Table 2. R versus square root value of P observed by the U manometer was plotted in Fig. 3. A good linear correlation was observed as expected for cases when the pressure drop across a valve can be described by the orifice equation.

The sizes of orifices were measured by:

(i) a microscope carried out by W.H. Dawson of this laboratory, and
(ii) an XL-815 optical comparator carried out by P. Cobill, Senior Quality Assurance Technician of AECL Chemical Company.

In carrying out measurement ii, other available orifices were also measured. The results are listed in Table 3. Number 13 to 16 are the orifices described in this report.

Using diameters measured by Dr. Dawson (Table 3), results shown in Fig. 2 and 3 and assuming the diameter ratio b $\sim$0 (defined in Eq. 2), from Eq. 4 the coefficient C_o for orifices No. 13 to 16 were estimated to be:

No.	C_o	d(mm)
13	0.686	0.410
14	0.633	0.788
15	0.710	1.000
16	0.644	1.318

Observed values of C_o are larger than 0.61 as expected for orifices in which the design is different from that for the maximum pressure drop and from perfect circular orifices. These results show why it is always emphasized in textbooks that "C_o is always determined experimentally" (1).

ESTIMATION OF SUPERFICIAL GAS VELOCITY

To measure the volumetric flow rate, V_G (Eq. 4), either pressure drop, ΔP, or recorder reading, R, and the gas density, d, must be monitored. In order to achieve these, the following measurements are usually carried out for the recycle gas stream during the pilot plant operation:

1. The square root of pressure drop across the orifice versus time.
2. The apparent hydrogen purity monitored by a Beckman hydrogen purity meter (on-line instrument).
3. Compositions of recycle gas samples at various conditions.

These results allow the computation of V_G at measuring conditions. But for planning pilot plant experiments, the gas density is not known and has to be estimated. We present a correlation to relate gas density with 'hydrogen purity' which is continuously monitored during experiments. This correlation was derived from previous experimental results.

MONITORED HYDROGEN PURITY

The hydrogen purity recorded by the Beckman meter was compared with the hydrogen concentration measured by gas chromatography for many runs carried out from 1981 to 1986. In general, the deviations are small. However, large deviations have been observed, possibly due to improper calibration. Therefore, the relation between the reading and actual hydrogen concentration must be established for each experimental series.

GAS DENSITIES

Gas densities for samples of the recycle gas stream were calculated for many runs by using the van der Waal equation. First order combination of specific volumes for individual gases was assumed. Figure 4 shows the plot

of density against hydrogen purity measured by GC. Those data were obtained for runs at the reaction temperature from 390°C to 460°C. The large scattering of data shown in Fig. 4 is not caused by the experimental uncertainty but is mainly caused by differences in the operating temperature. At a given hydrogen concentration, the density of recycle gas density (at 20°C) decreases as the reactor temperature increases. This is because the recycle gas at higher hydrocracking severity contains more heavy gaseous molecules.

Since the difference in gas densities at the same hydrogen concentration for reactor temperatures from 430°C to 460°C is about the magnitude of the experimental uncertainty, a linear correlation was derived for reaction temperature $\geq$430°C:

$$d_R = 0.1083 - 9.8 \times 10^{-4} [H_2] \qquad \text{Eq. 5}$$

where

$[H_2]$ = the actual hydrogen purity
subscript R: for room temperature (20°C)

At lower temperatures (<430°C), the density was usually higher than that predicted by Eq. 5.

VOLUMETRIC FLOW RATE CURVES

Equations 4 and 5 were used to generate relations for gas flow rate reading R with volumetric flow rate V_G at 100% and 85% hydrogen purities (Fig. 5 and 6). These conditions are frequently used in pilot plant experiments.

SUPERFICIAL GAS VELOCITY

Superficial gas velocity (SFGV) is defined at the volumetric gas flow rate divided by the cross-sectional area of the column. The operation at high temperatures causes a large amount of products to be vaporized (2), which results in uncertainty in determining SFGV. However, because the average molecular weight of products is large, it is reasonable to assume that the contribution of vaporization is small and can be neglected.

The SFGV can be estimated by:

$$SFGV = V_G \cdot d_R / D_T \qquad \text{Eq. 6}$$

where indices R and T are for room and reaction temperatures, respectively.

Because the gas density for room temperature was estimated by the van der Waal equation, it would be most reasonable to estimate the density at reaction temperature by the same equation. However, because d_R is usually evaluated at the same pressure of d_T, e.g., Fig. 4, if D_R/d_T is replaced by the ratio of reaction to room temperature (in K), the deviation will be only about 0.3% of the actual value.

DISCUSSION

Most of the data (Fig. 4) used in the derivation of the correlation (Eq. 5) was based on results of runs carried out before 1984. The correlation predicts recycle gas densities well for later runs in which many were randomly chosen for comparison. The band of data shown in Fig. 4 qualitatively represents the effect of temperature. The range is from 390°C to 450°C respectively corresponding to the upper and lower bounds of the densities of the same hydrogen purity.

The density correlation is recommended for estimating SFGV to plan pilot plant experiments. The actual SFGV of experiments can be calculated by the same procedure by using gas densities determined experimentally.

Because the orifices are very small, a small difference in size will result in a significant difference in the reading for the same gas rate. We therefore strongly recommend that any orifice to be used should be calibrated.

ACKNOWLEDGEMENT

The author sincerely thanks the pilot plant crew for their assistance in carrying out the experiment and W.H. Dawson (CANMET) and P. Cobill of AECL for measuring orifice sizes.

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Table 1 - Observed volumetric flow rates

Square root meter reading	Volumetric rate (L/h) for orifice number			
	13	14	15	16
40	28.56	100.83	185.54	293.65
50	35.58	120.51	228.80	360.20
60	44.15	149.76	272.97	436.01
70	51.10	174.96	314.15	504.52
78	-	-	-	574.16
80	58.83 58.27	199.87	375.60	-
87	-	-	-	645.55
90	65.45	223.46	402.91	-
96	69.33	235.48	425.42	-

Table 2 - Pressure drop and square root readings observed in orifice calibrations

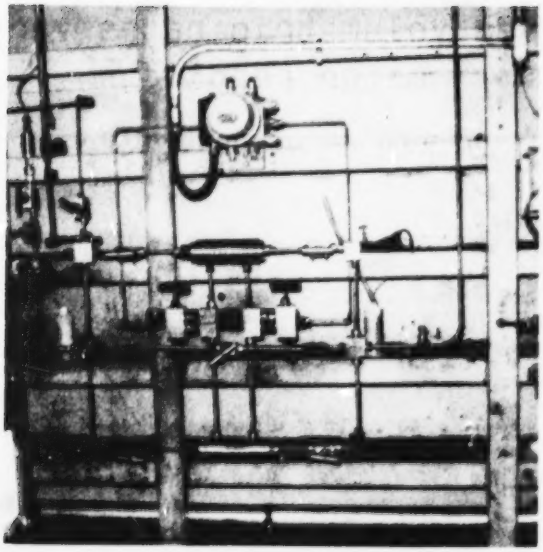
Square root reading (R)	Pressure drop Inches of water	Square root of pressure drop	$R / P^{1/2}$
49.0	27.63	5.26	9.32
52.5	32.06	5.66	9.27
76.3	66.25	8.14	9.37
84.2	81.31	9.02	9.34
62.0	44.75	6.69	9.27
39.8	18.13	4.26	9.35
60.0	41.88	6.47	9.27
86.0	85.06	9.22	9.32
69.5	55.87	7.48	9.30
59.1	40.44	6.36	9.29
72.5	60.5	7.78	9.32
85.5	83.69	9.15	9.35
Average			9.31 ± 0.04

Table 3 - Apparent diameter of orifices measured by optical comparator and microscope

Orifice nNumber	Size in inches	
	Comparator*	Microscope**
1	0.0395	-
2	0.0312	-
3	0.0314	-
4	0.0504	-
5	0.0285	-
6	0.0283	-
7	0.0390	-
8	0.0282	-
9	0.0292	-
10	0.0309	-
11	0.0284	-
12	0.0286	-
13	0.0152	0.0160
14	0.0281	0.0310
15	0.0392	0.0394
16	0.0502	0.0519

* Measured by P. Cobill of AECL Chemical Company.
** Measured by W.H. Dawson, ERL, CANMET.

A.



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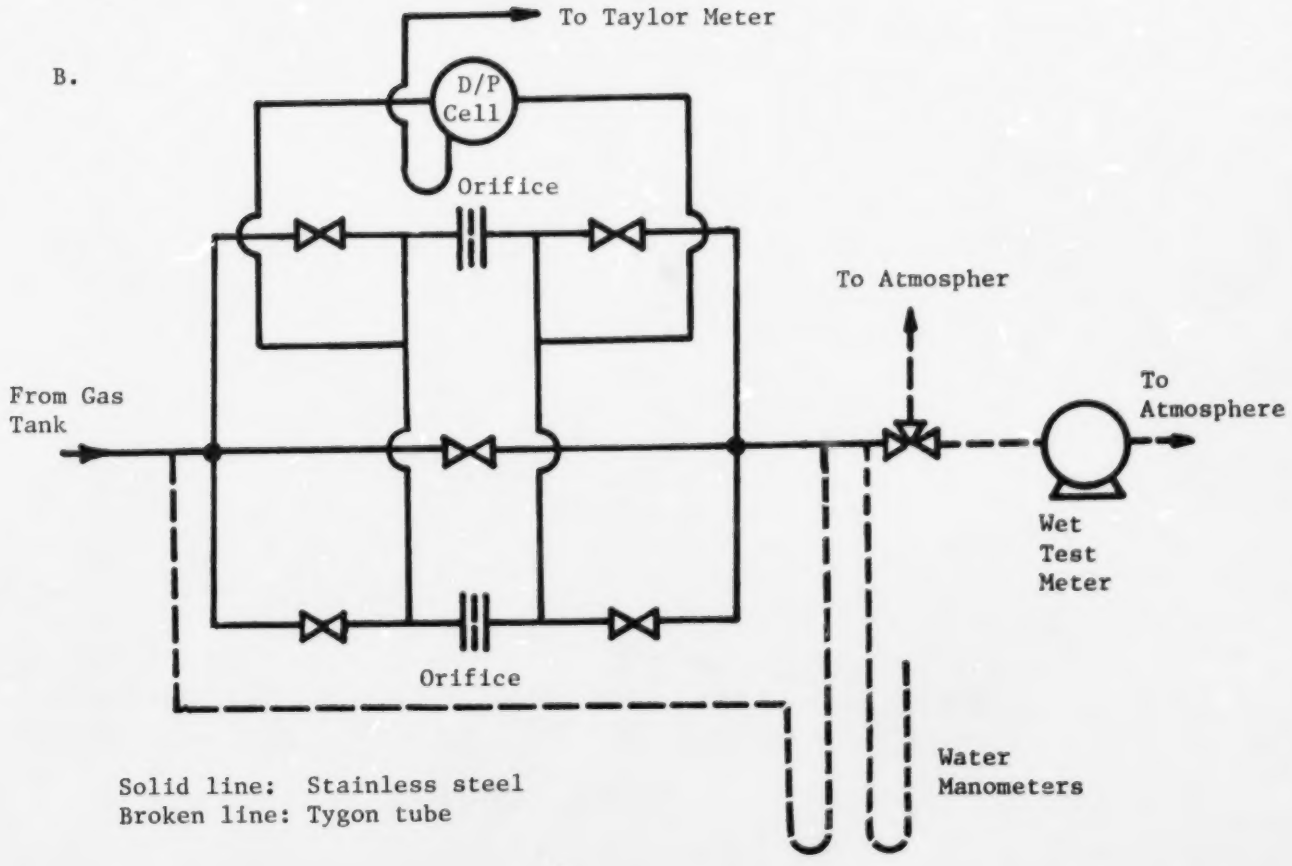

Fig. 1 - Setup of orifice systems in the CANMET hydrocracking pilot plant (A) and the schematic of setup for calibration.

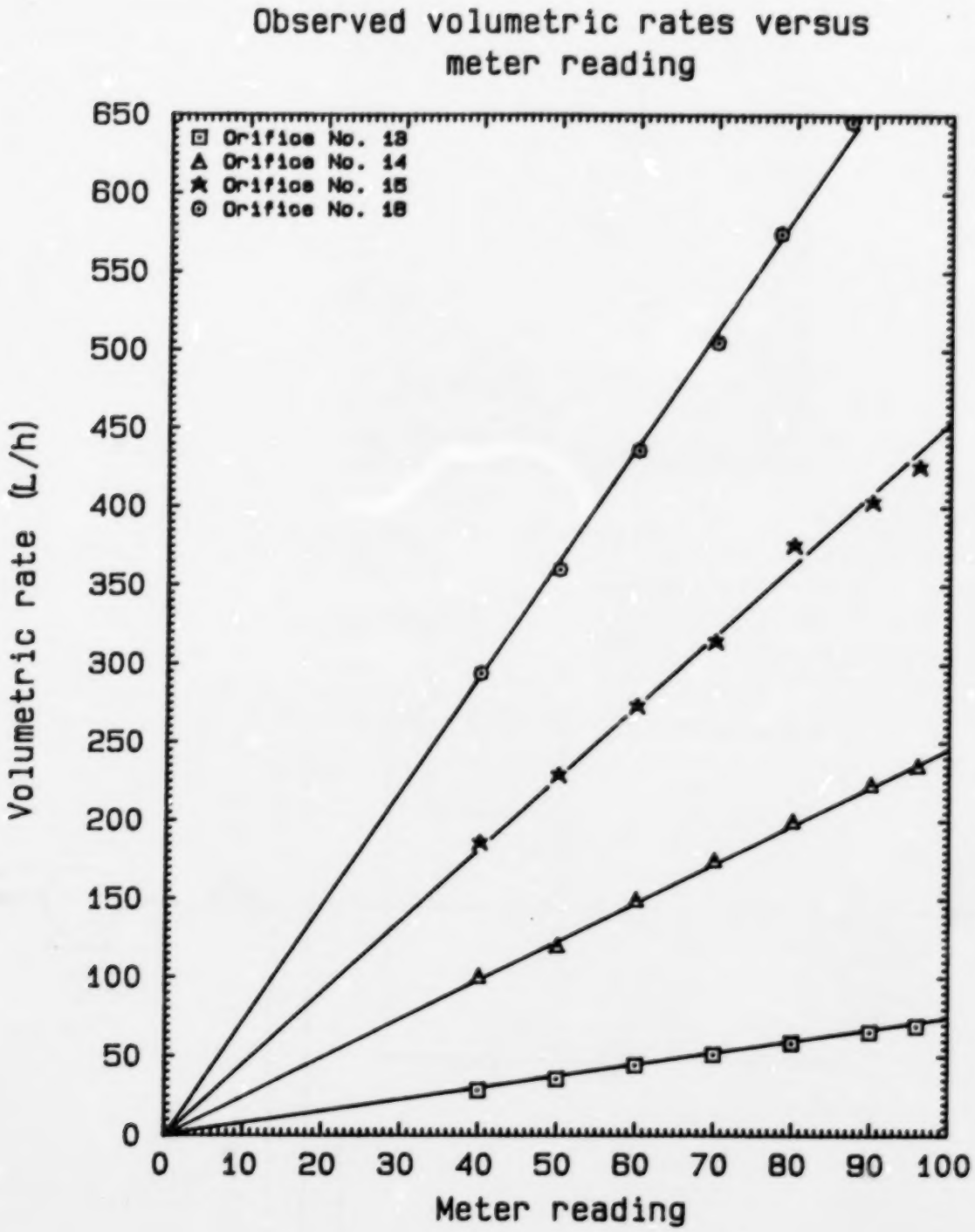

Fig. 2 - Observed volumetric flow rates using nitrogen at ambient conditions

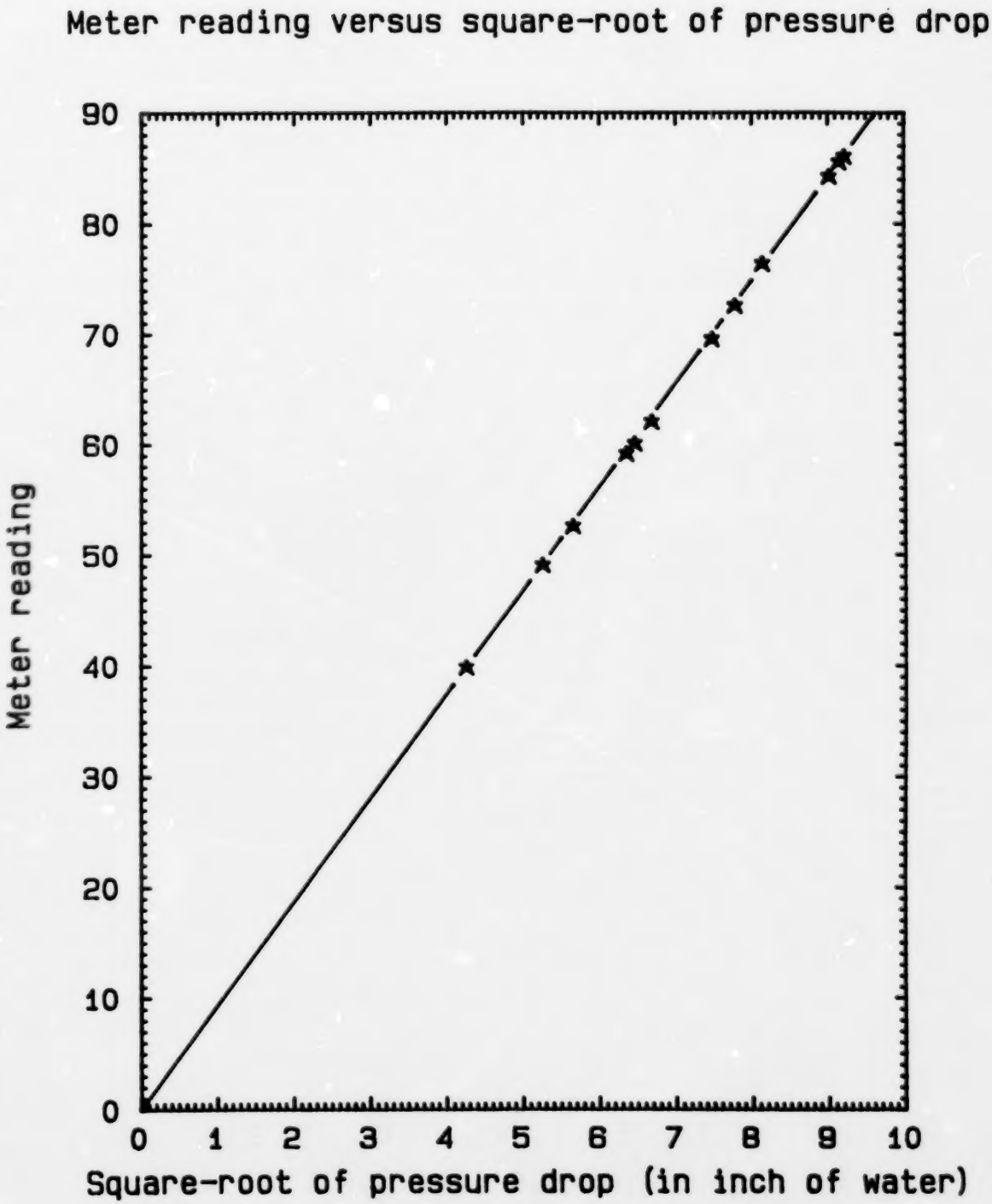

Fig. 3 - Correlation of Taylor instrument reading with the pressure drop

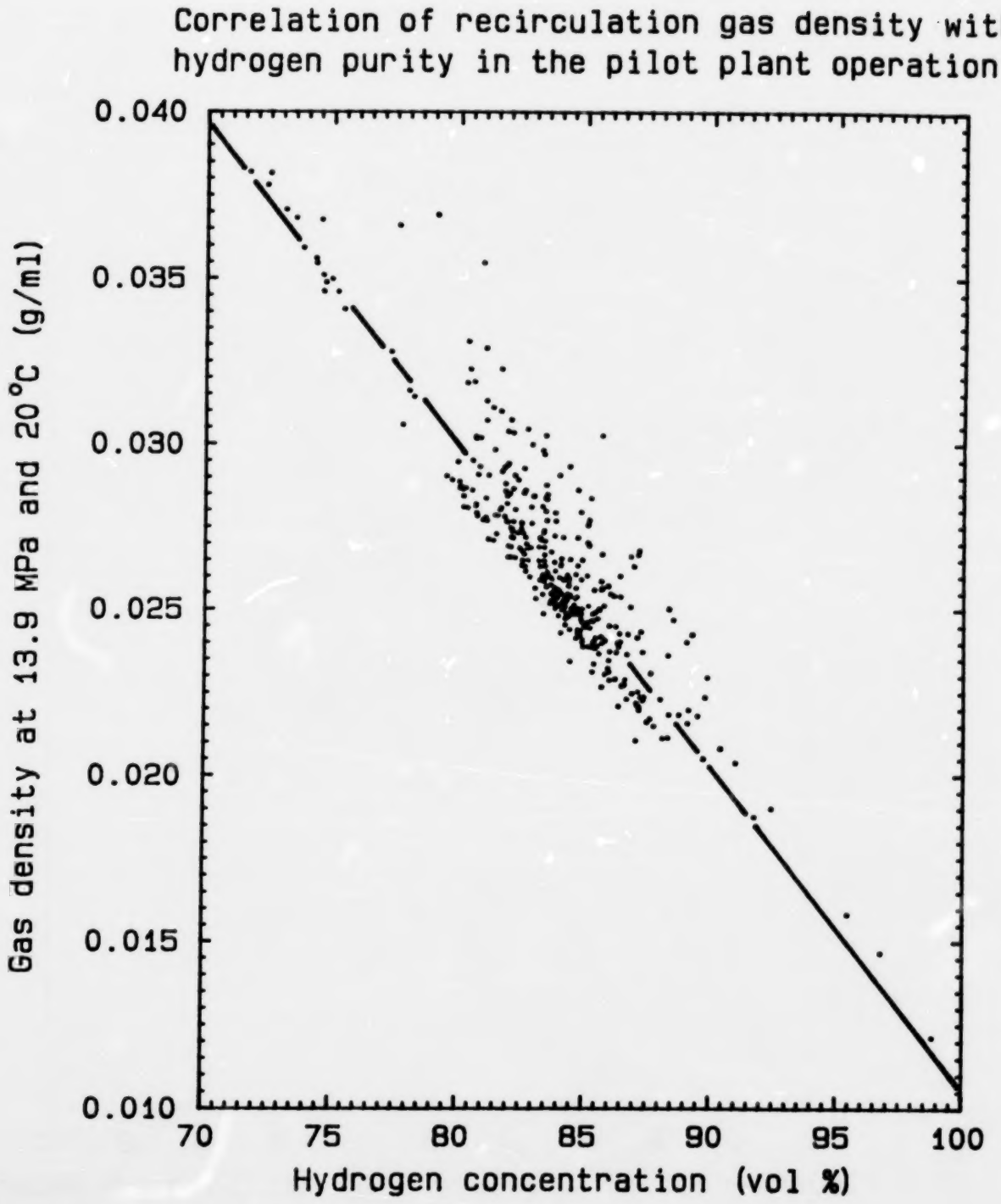

Fig. 4 - Observed recycle gas density as function of hydrogen purity in the CANMET hydrocracking pilot plant operation and the recommended correlation for temperature ≥430°C

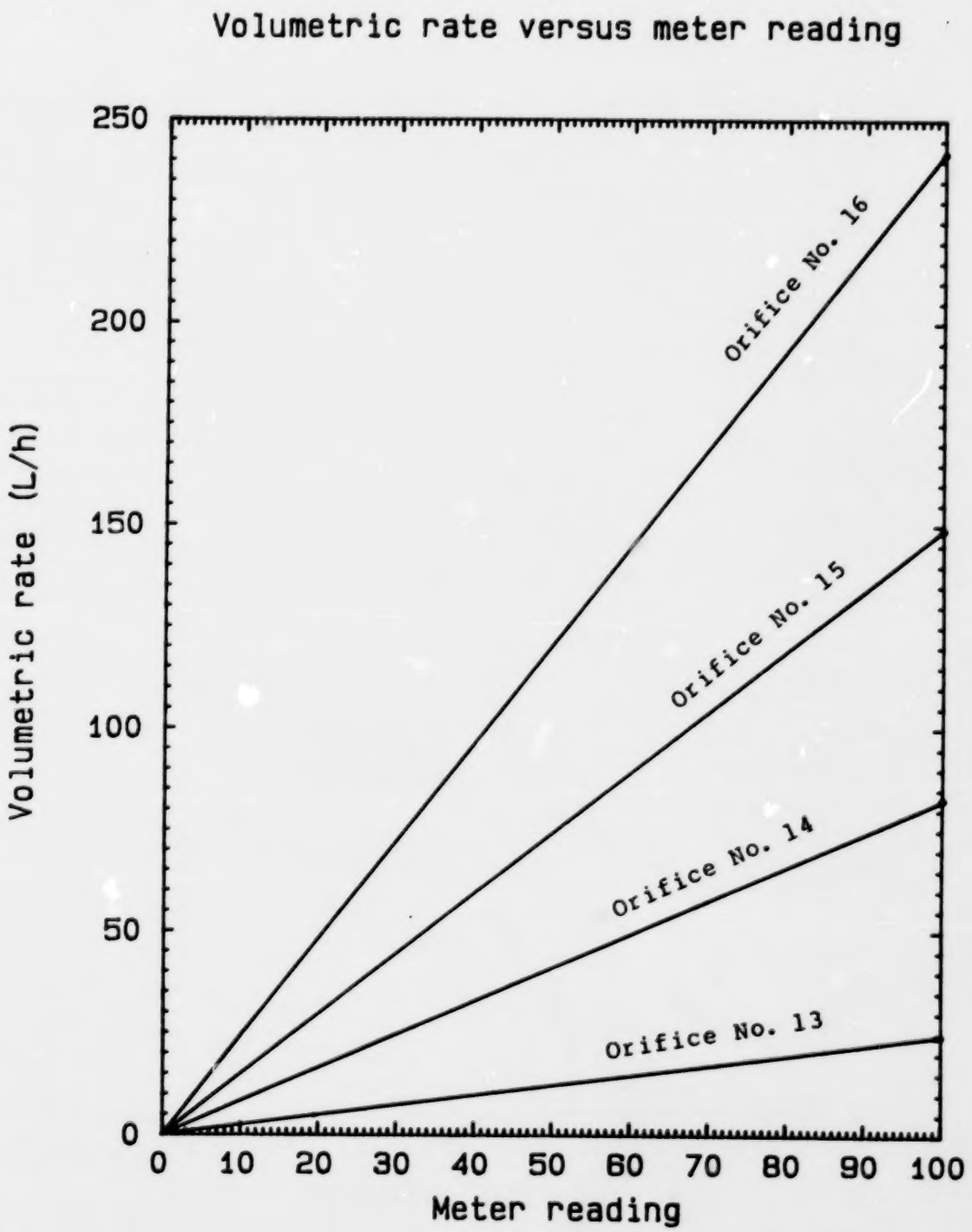

Fig. 5 - Volume flow rate of pure hydrogen at 13.9 MPa as function of Taylor meter reading for calibrated orifices

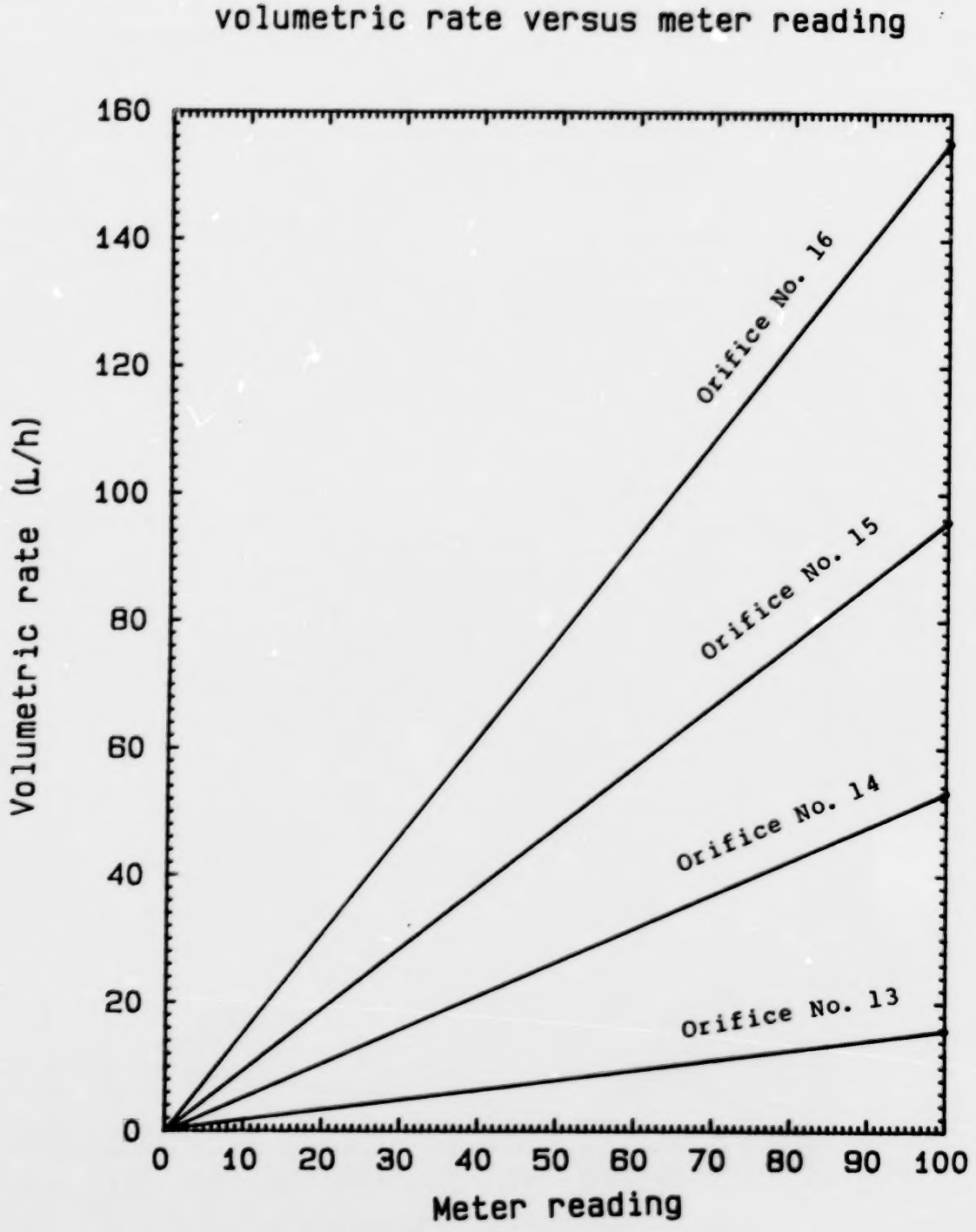

Fig. 6 - Correlation of flow rate of 85% hydrogen in the recirculation stream of the pilot plant operation as function of Taylor meter reading for calibrated orifices